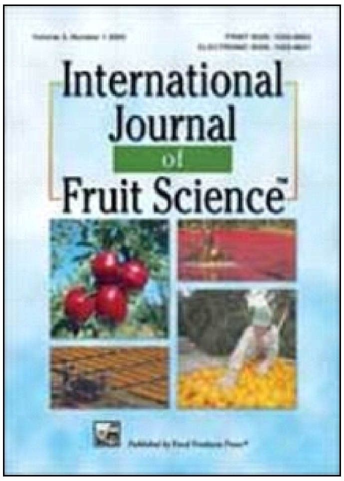


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# Evapotranspiration Rates and Crop Coefficients for Lowbush Blueberry (Vaccinium angustifolium)

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# Evapotranspiration Rates and Crop Coefficients for Lowbush Blueberry (*Vaccinium angustifolium*)

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**ABSTRACT.** Lowbush blueberry (*Vaccinium angustifolium*) yield is strongly influenced by water availability; however, growers need more specific irrigation recommendations in order to optimize water use efficiency. Weighing lysimeters were used to determine actual evapotranspiration (ET) rates of lowbush blueberry at one nonirrigated and two irrigated sites within 7 km of the Maine coast. For the three-year study period, overall mean weekly ET rates (with standard errors) during June,

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July, and August were calculated to be 2.13 (±0.05), 2.39 (±0.07), and 2.19 (±0.07) cm/wk, respectively. Mean monthly ET rates did not differ significantly between irrigated and nonirrigated sites. Crop coefficient ($K_c$) values were determined from the ratio of daily Penman-Montieth grass reference ET to measured daily ET. The combined mean monthly $K_c$ values for the two irrigated sites varied between 0.61 and 0.74 from May through September, with an overall mean $K_c$ value for all sites of 0.69 (±0.02). The $K_c$ values showed no significant rotation-year component. Consequently, the $K_c$ value determined in this study can be used in conjunction with meteorological data to provide Maine lowbush blueberry growers with the ability to better predict water demand by their crop. Fog at the irrigated sites was found to contribute approximately 13.5 cm of net water equivalent per growing season. However, the effects of dew formation and fog deposition are already reflected in the $K_c$ value for each site, enabling growers to determine water demand from these values and grass reference ET data alone. These findings may substantially contribute to improved water use efficiency for irrigated lowbush blueberry in Maine.

**KEYWORDS.** Evapotranspiration, crop coefficient, lowbush blueberry, *Vaccinium angustifolium*, fog deposition, Maine

## *INTRODUCTION*

In 2007, lowbush blueberry production in North America totaled over 82,486 metric tons (90,925 tons), with about 41% of this crop produced within the state of Maine (Univ. Maine Coop. Ext., 2008). North American lowbush blueberry production has grown on average by more than $2.27 \times 10^3$ metric tons (~2500 tons) per year since the mid-1980s. Increased blueberry production in Maine is largely associated with improved practices for managing the state's existing land base of approximately 24,300 hectares (60,000 acres) of lowbush blueberry cropland (Yarborough, 2004).

Improved water use efficiency has long been viewed as a potentially cost-effective management approach for increasing lowbush blueberry yield. Efficient irrigation management begins with an understanding of the amount of water used by a crop species in the process of evapotranspiration (ET). By measuring the changes in weight of an isolated plant-soil system, weighing lysimeters allow for the determination of actual ET rates for that particular cropping system. These data can then be used in conjunction with Penman-Montieth reference evapotranspiration ($ET_o$) rates obtained from meteorological data to calculate crop coefficient ($K_c$) values.

Crop coefficients are an important tool for irrigation management because they represent the ratio of actual crop ET to $ET_o$ and therefore allow for the calculation of crop water use from meteorological data alone. This is valuable because the expensive and labor-intensive nature of weighing lysimeters makes them mostly useful as research tools that are generally impractical for growers needing to make daily irrigation decisions. Although $K_c$ values have been determined for many agricultural crops, $K_c$ values for lowbush blueberry are currently unknown. Thus, the specific water demands of lowbush blueberry under varying climatic conditions are largely based on tradition and regional rules of thumb. Maine growers who have gone to the expense of irrigating during the growing season have typically tried to supplement rainfall to ensure that approximately 2.54 cm (one inch) of water per week reaches their crop (Starr et al., 2004). Though this and other traditional guidelines have generally proven successful, evolving climatic, economic, environmental, and legislative forces make it incumbent on blueberry growers to utilize the most efficient production practices available.

It is generally believed that the more geographically proximate a blueberry field is to the Atlantic coast, the lower the field's irrigation requirements, due primarily to lower temperature and greater incidence of fog closer to the coast. The important role of fog deposition in providing water to vegetation as a supplement to rain has been shown in many areas of the world. For example, the importance of fog to the water budget of northern California coastal redwood forests (*Sequoia sempervirens*) has been well documented (Burgess and Dawson, 2004; Dawson, 1998; Ingraham and Matthews, 1995). The coast of Maine, like the northern coast of California, is frequently engulfed in summer advection fog, as moisture from warm Gulf Stream winds condenses upon meeting the colder waters of the Gulf of Maine. In addition to fog, the generally high relative humidity and large diurnal temperature fluctuations in Maine often favor formation of early morning dew throughout the state. However, the effects of fog deposition and dew formation on water budgets of Maine lowbush blueberry have not yet been sufficiently quantified.

The objective of this research was to determine lowbush blueberry ET rates and $K_c$ values using weighing lysimeters, soil water assessments, and meteorological measurements. These investigations were conducted at both irrigated and nonirrigated sites in order to determine how irrigation influences these properties. In addition, the influence of fog deposition and nighttime dew formation on the water requirement of lowbush blueberry was examined.

## *MATERIALS AND METHODS*

### *Research Sites*

Research was conducted at the University of Maine's Blueberry Hill experimental farm (BBH) in Jonesboro, Maine, and at a farm located approximately 5.8 km away in Addison, Maine. Both experimental sites were approximately 7 km from the Maine coast. The BBH site contained two research stations located approximately 100 m apart and was maintained in alternate crop rotation cycles, whereas the Addison site contained one research station only. Each research station contained four weighing lysimeters installed several meters apart in a rectangular orientation around a central climate/data logger station. The climate/data logger station contained a Campbell Scientific (Logan, Utah, USA) CR10X data logger, which recorded both meteorological data (60-min average frequency) and average changes in lysimeter weight (10-min frequency). The measured meteorological data included air temperature and relative humidity (Campbell Scientific HMP45C temperature and RH probe), solar radiation flux (Campbell Scientific LI200X pyranometer), wind speed (Campbell Scientific 03003 Wind sentry), precipitation (Texas Instruments TE525, Texas Instruments, Dallas, Texas, USA), and visibility (Belfort 6000, Belfort Instruments, Baltimore, Maryland, USA). These meteorological data were used to determine the daily Penman-Montieth reference $ET_o$ rates (Allen et al., 1998). In addition, Spectrum Watermark model 450 data loggers with relative humidity, air temperature, leaf wetness, and soil moisture sensors recorded data at all stations beginning in July 2007.

Soil at BBH is classified as a Colton gravelly sandy loam (sandy skeletal, isotic, frigid Typic Haplorthod) with 0% to 3% slopes. These soils are excessively drained and have a depth to water table of greater than 203 cm (80 in). The soils at BBH have been farmed and managed extensively for over 50 years and have an overlying O-horizon (Seymour et al., 2004). Conversely, the Addison site has soils classified as a complex of Buxton (fine, illitic, frigid Aquic Dystric Eutrudept) and Lamoine (fine, illitic, nonacid, frigid Aeric Epiaquept) soil series formed from glaciolacustrine and/or fine glaciomarine deposits. The top 0 to ~20 cm of these soils are described as mixtures of silty clay loams and silty clays. These soils are less well drained than those at BBH and have higher slopes (3% to 15%), lower hydraulic conductivity, and water tables that are closer to the surface (46 to 76 cm). The finer textured soils at Addison were chosen to offer a contrast from the coarser BBH soils.

Soil volumetric water content was measured at BBH in 2006 and 2007 using time domain reflectometry (TDR) probes. In addition, soil water matric potential was monitored at all stations beginning in July 2007 using soil transducers. At BBH, tensiometers (eight per station) measured soil water matric potential both inside and immediately adjacent to each lysimeter. Irrigation was applied at BBH when the average soil matric potential of the outside tensiometers decreased below –20 kPa. The irrigation system at BBH consisted of raised sprinkler heads atop movable piping. No irrigation was applied to the Addison station during the study period.

## *Weighing Lysimeters*

The 12 weighing lysimeters used in this study were constructed as detailed by Storlie and Eck (1996) and Starr et al. (2004). Briefly, the lysimeter design featured a rectangular inner chamber constructed from 1.91-cm (0.75-in)-thick treated plywood inside an outer chamber frame constructed from 3.18-cm (1.25-in)-thick treated plywood. The inner chamber, containing soil and blueberry plants, rested upon a single ball bearing that was centered atop a temperature-compensated weighing load cell. Outside surfaces of the inner chamber were treated with fiberglass cloth and resin. The inner chamber of each lysimeter had dimensions of 46 cm × 46 cm (18 in × 18 in) with a surface area of 0.21 $m^2$ (2.25 $ft^2$) and a depth of 44.5 cm (17.5 in), giving a total internal volume of 0.94 $m^3$ (3.28 $ft^3$). Four small, rigid springs were positioned between the inner and outer chambers to prevent contact between the two chambers. A drainage collection system, consisting of perforated piping, was run from the bottom of the inner chamber to a carboy positioned in an access port adjacent to the outer chamber. Drainage was periodically measured to assess and monitor the water-holding capacity of each lysimeter. Lysimeter accuracy was tested periodically during each growing season using calibration weights, and errors in mass measurements were generally less than 2%.

## *Data Analysis*

The 10-minute changes in weight for each lysimeter were summed into hourly changes. Hourly changes in lysimeter weight at a particular site were then eliminated if the rain gauge at the site indicated any precipitation for that hour or, alternatively, records indicated the application of irrigation for that hour. The elimination of these “rain hours” rather than entire “rain days” allowed for the use of a much larger data set. In addition, the inclusion of all days eliminated the bias of using only “dry” days of generally greater solar flux. As in all lysimeter studies, data associated with excessive drainage, site flooding, animal activity, or similar perturbations to the experimental conditions were eliminated from consideration. In total, 3.83% of the 84,628 total hours of lysimeter data from the BBH stations, and 7.54% of the 44,384 total hours of lysimeter data from the Addison station were discarded based on these quality control criteria.

Due to the close proximity (~5.8 km) of Addison to BBH, the Penman-Montieth grass reference $ET_o$ rates (Allen et al., 1998) for both sites were calculated from the meteorological data collected at BBH. Daily and weekly crop coefficients were calculated by dividing the lysimeter determined ET rate for a particular time period by the climate coupled $ET_o$ rate for the same period. The blueberry plants generally covered the entire surface area of the lysimeters during the months of June through September, and thus the land area used to calculate $K_c$ values was 0.21 $m^2$.

### *Statistical Analysis*

Pearson correlations were used to examine the relationship between ET and $ET_o$ rates within the same station, as well as the degree of differential ET response to meteorological factors among separate stations. Student’s t-tests and analysis of variance with Tukey’s mean separation analysis were utilized to test the statistical significance of ET rates, $ET_o$ rates, and $K_c$ values between stations.

## *RESULTS AND DISCUSSION*

### *Jonesboro Climate and Reference ET*

Selected climatic characteristics for research stations located at the Blueberry Hill Experimental farm in Jonesboro, Maine (BBH), are given in Table 1. Based upon the 60-year data given in the table, rainfall amounts at BBH for the six-month period of April to September are typically greatest for the cooler months of April, May, and September and lowest for the warmer months of June, July, and August. Data for the individual years, however, illustrate the wide variation in monthly precipitation observed during this three-year period. The month of July 2006, for example, was particularly wet, with many moderate precipitation events that deposited an amount of rainfall that was more than three times greater than the long-term

TABLE 1. Selected meteorological characteristics at Blueberry Hill Experimental Farm, Jonesboro, Maine, for the months of April through September (2005–07)

| Year | Month | Data days | Total rain (cm) | 60-Yr* total rain (cm) | Mean air temp. (°C) | Mean rel. humidity (%) | Mean solar flux (mJ/m$^2$) | Mean wind speed (m/s) | Mean reference ET (cm/wk) |
|---|---|---|---|---|---|---|---|---|---|
| 2005 | | | | | | | | | |
| | April | 24 | 16.0 | *11.3* | 5.9 | 81.9 | 17.1 | 2.8 | 2.05 |
| | May | 31 | 19.3 | *10.6* | 8.4 | 91.6 | 13.5 | 2.2 | 1.93 |
| | June | 30 | 4.1 | *9.1* | 15.3 | 93.9 | 20.8 | 2.0 | 3.74 |
| | July | 31 | 4.3 | *8.2* | 18.2 | 90.9 | 23.7 | 1.9 | 3.56 |
| | August | 31 | 10.9 | *7.6* | 18.4 | 93.6 | 21.9 | 1.7 | 3.16 |
| | September | 26 | 6.1 | *10.0* | 16.3 | 93.0 | 17.7 | 2.2 | 2.43 |
| 2006 | | | | | | | | | |
| | April | 30 | 6.4 | *11.3* | 6.2 | 70.4 | 15.9 | 3.2 | 1.96 |
| | May | 31 | 11.7 | *10.6* | 11.0 | 79.7 | 17.0 | 2.4 | 2.69 |
| | June | 30 | 32.0 | *9.1* | 8.7 | 94.2 | 13.0 | 1.8 | 2.39 |
| | July | 31 | 17.8 | *8.2* | 15.5 | 88.6 | 20.2 | 2.7 | 3.45 |
| | August | 31 | 6.9 | *7.6* | 15.5 | 82.6 | 16.8 | 2.0 | 2.81 |
| | September | 27 | 4.1 | *10.0* | 12.1 | 85.0 | 14.4 | 2.0 | 1.98 |
| 2007 | | | | | | | | | |
| | April | 13 | 41.7 | *11.3* | 7.0 | 74.8 | 17.2 | 2.8 | 2.05 |
| | May | 27 | 9.9 | *10.6* | 10.0 | 83.5 | 18.9 | 2.6 | 2.50 |
| | June | 28 | 7.1 | *9.1* | 14.8 | 82.6 | 19.7 | 2.2 | 3.05 |
| | July | 26 | 8.4 | *8.2* | 12.4 | 92.3 | 18.4 | 2.0 | 2.79 |
| | August | 20 | 8.4 | *7.6* | 15.5 | 88.2 | 18.5 | 2.1 | 2.85 |
| | September | 22 | 5.3 | *10.0* | 12.8 | 88.9 | 14.4 | 2.1 | 1.87 |

*Italic values represent 60-year mean values.

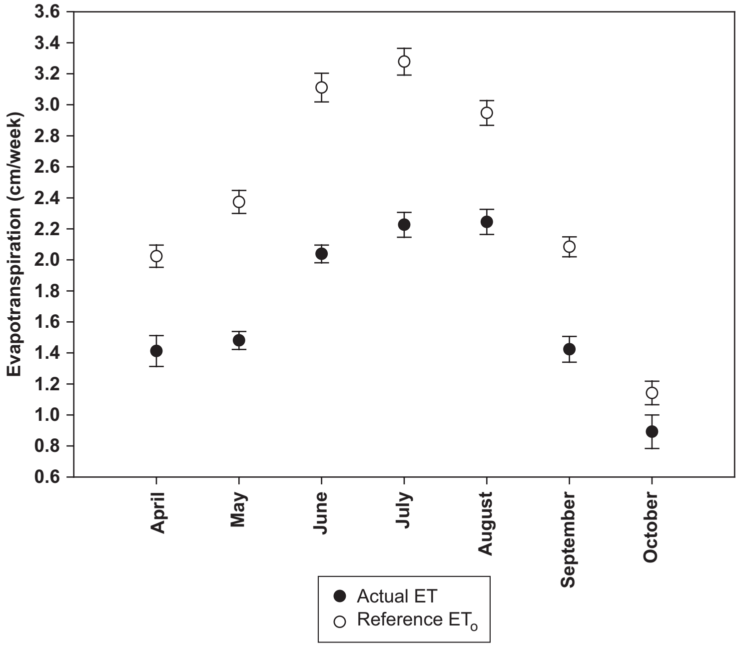
mean total for July. The effects of this abundant precipitation can be seen in the lower mean values of air temperature, solar flux, and $ET_o$ rates recorded for that month at BBH (Table 1). The duration of precipitation also affected the magnitude of the other climatic parameters given in the table. For instance, the unusually large rainfall total for the month of April 2007 was due largely to a single storm, which produced in excess of 25.4 cm (10 in) of rain early in the month (Univ. Maine Coop. Ext., 2008). Because the rain was not spread over the course of the month in smaller, multiple events, the mean values of air temperature, solar flux, and $ET_o$ for April 2007 are consistent with the values recorded for April during 2005 and 2006.

For the three-year study period, daily mean relative humidity at BBH was 87.4%, with a minimum daily mean of 75.4% during April and a maximum daily mean of 93.5% during July. Solar radiation input was greatest during the months of July and August, with mean daily flux rates of 19.8 MJ $m^{-2}$ and 17.9 MJ $m^{-2}$, respectively. Wind speed was relatively consistent during the study period, with a daily mean speed of 2.3 m $s^{-1}$. Weekly $ET_o$ rate at BBH, when averaged for each month over the course of the 2005–07 growing seasons (April through August), ranged between 2.02 cm (0.79 in)/wk and 3.28 cm (1.28 in)/wk, with the greatest rates generally occurring in July and the lowest rates occurring in April. From June through August, $ET_o$ rate at BBH averaged 3.12 cm (1.23 in.)/wk and was less than 2.54 cm (1 in)/wk only during the wettest month of June 2006. These $ET_o$ rates are consistent with the mean $ET_o$ rate of 3.38 cm (1.33 in.)/wk found by Seymour et al. (2004) for an eight-week period from 23 June to 18 August 2002 at BBH. Figure 1 illustrates $ET_o$ and ET rates for BBH using all of the data from the 2005 to 2007 seasons. Differences between the two ET rates were greatest from June through August, when water demand was highest, and became minimal at the end of the growing season when water demand was lowest.

## *Irrigation*

Above-ground sprinkler irrigation was used at BBH during the 2005–07 growing seasons for both prune and crop fields. For the 2005–07 growing seasons, irrigation at Jonesboro averaged 1.02 cm (0.40 in.), 4.52 cm (1.78 in), and 4.80 cm (1.89 in.) in June, July, and August, respectively. During this same period, irrigation applied to prune fields averaged 0.89 cm (0.35 in), 3.86 cm (1.52 in.), and 3.58 cm (1.41 in.), respectively. In 2005, 1.98 cm (0.78 in.) of water was applied to the BBH prune field in one irrigation event during September. The Addison site was not irrigated during the period of this study.

FIGURE 1. Mean weekly evapotranspiration rates recorded for each month during the 2005–07 growing seasons at Blueberry Hill Experimental Farm in Jonesboro, Maine (error bars denote standard error of the mean).






## *Actual Evapotranspiration*

Mean weekly ET rates during hours of no rain or irrigation were determined from the weighing lysimeter data and are presented on a monthly basis in Table 2. Addison and both BBH sites generally had similar mean weekly ET rates. The maximum mean weekly ET rate was observed in July at 3.00 cm/wk (1.18 in)/wk, whereas the minimum mean weekly ET rate of 0.94 cm (0.37 in)/wk occurred during April and September. Mean weekly ET rates for all sites generally exceeded 2.0 cm/wk (~0.8 in/wk) in June, July, and August. Interestingly, these ET rates (Table 2) are in general agreement with the approximately 2.54 cm (1 in)/wk of rainfall that Maine lowbush blueberry growers deem sufficient for their crops during the driest months of the growing season.

Daily ET rate comparisons represent a statistically more powerful means of comparing ET rates of different stations than do weekly comparisons.

TABLE 2. Mean weekly evapotranspiration rates (cm/wk) for each month as determined using weighing lysimeter data obtained from BBH and Addison experimental stations during the 2005–07 growing seasons

| Location | April | May | June | July | August | September |
|---|---|---|---|---|---|---|
| 2005 | | | | | | |
| Jonesboro BBH 1 (P)[z] | 1.04 (404)[y] | 1.32 (572) | 1.37 (619) | 1.80 (666) | 2.39 (540) | 1.52 (564) |
| Jonesboro BBH 2 (C) | 1.19 (404) | 1.85 (573) | 1.91 (662) | 2.08 (694) | 2.21 (664) | 1.88 (405) |
| Addison (C) | 1.02 (55) | 1.91 (566) | 2.16 (653) | 2.21 (600) | 1.78 (682) | 1.40 (588) |
| 2006 | | | | | | |
| Jonesboro BBH 1 (C) | 1.35 (644) | 1.75 (649) | 2.44 (552) | 2.67 (562) | 1.93 (615) | 1.14 (576) |
| Jonesboro BBH 2 (P) | 1.55 (642) | 1.70 (649) | 2.39 (555) | 3.00 (596) | 2.18 (629) | 0.94 (575) |
| Addison (P) | 0.94 (353) | 1.27 (652) | 2.21 (566) | 2.90 (685) | 2.13 (680) | 1.24 (678) |
| 2007 | | | | | | |
| Jonesboro BBH 1 (P) | 1.83 (279) | 1.32 (616) | 2.16 (673) | 2.24 (571) | 2.29 (454) | 1.55 (494) |
| Jonesboro BBH 2 (C) | 2.18 (280) | 1.52 (616) | 2.34 (629) | 2.34 (568) | 2.49 (427) | 1.85 (490) |
| Addison (C) | 1.45 (273) | 1.09 (669) | 2.18 (659) | 2.26 (660) | 2.31 (666) | 1.96 (663) |
| Three-year mean | | | | | | |
| Jonesboro BBH 1 | 1.35 (1327) | 1.54 (1837) | 1.97 (1844) | 2.21 (1799) | 2.20 (1609) | 1.39 (1634) |
| Jonesboro BBH 2 | 1.57 (1326) | 1.69 (1838) | 2.20 (1846) | 2.46 (1858) | 2.27 (1720) | 2.07 (2028) |
| Addison | 1.19 (681) | 1.39 (1887) | 2.20 (1878) | 2.50 (1945) | 1.50 (1470) | 1.57 (1929) |

[z]Evapotranspiration rates determined in the crop (C) and prune (P) year rotations.
[y]Data are given as mean weekly ET rate (cm/wk) for each month, followed by the number of hours on which that rate was determined.

However, due to the strong dependence of ET rate on meteorological conditions, this approach necessitates that daily comparisons between stations be made only on data recorded on concurrent days. Thus, gaps in the available data at any one station reduce the number of days that may be used for comparison. An analysis of variance using only days in common for the three-year study period revealed significant ($P < 0.05$) differences in daily mean ET rates between stations in April, May, and June. For the first two of these months, BBH 2 had greater daily mean ET rates than BBH 1 or Addison, whereas in June, BBH 2 and Addison had significantly greater daily mean ET rates than BBH 1. Despite these early season differences, mean daily ET rates for the overall "days in common" data were found to be similar for all three stations.

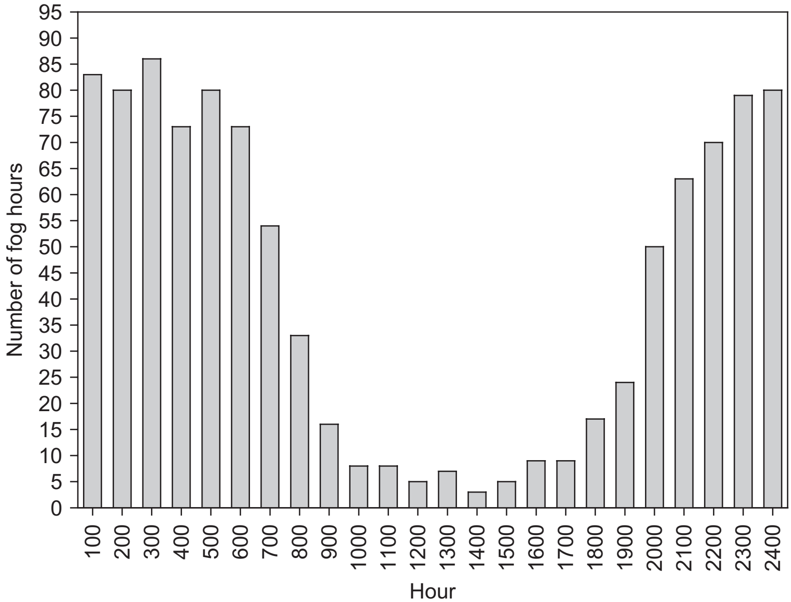
Mean daily ET rates (with standard errors) from April to August (2005–07) were determined to be 0.256 ± 0.007 cm (0.100 ± 0.002 in)/day, 0.280 ± 0.007 cm (0.109 ± 0.002 in)/day, and 0.268 ± 0.008 cm (0.102 ± 0.002 in)/day for BBH 1, BBH 2, and Addison, respectively. These rates are comparable to the daily mean ET rate of 0.270 cm (0.106) in/day (with a coefficient of variability of 71%) calculated by Starr and Yarborough (2006) for the period 11 July to 8 October 2003 from lysimeter data collected at BBH. Although the two studies report results for different time periods, the lower ET rates associated with the months of April and May in the present study appear to offset the lower September and October ET rates of the previous study.

The three-year overall correlation between daily mean ET rate at BBH 1 and BBH 2 was 0.835, indicating similar water loss patterns despite offset rotation cycles. The correlation in daily mean ET rate was stronger between BBH 2 and Addison (0.639) than between BBH 1 and Addison (0.547), a result consistent with the equivalent cropping cycles shared by Addison and BBH 2. Correlations between daily mean ET and $ET_o$ rates were higher for BBH 2 (0.685) compared to BBH 1 (0.533). This may be due to the effect of the prune rotation for two of the three study years at the BBH 1 station, which could have led to an attenuated early season ET climatic response during the early months of the 2005 and 2007 growing seasons. Despite these early season differences in daily mean ET rate at BBH 1 compared with BBH 2, no statistically significant differences were observed in the mean daily ET rate of crop fields as compared with prune fields.

## *Fog Deposition*

Figure 2 illustrates the hourly distribution of non-rain, heavy fog events occurring at BBH over the course of 14,255 hours during the 2005

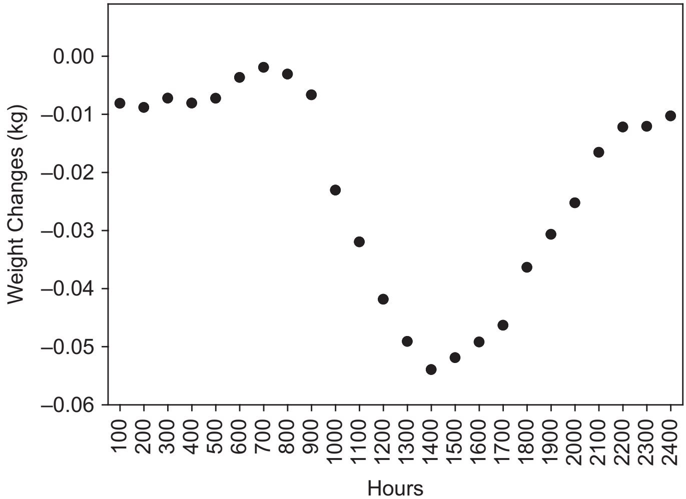
FIGURE 2. Instances of heavy fog (visibility < 1 km) at Blueberry Hill Experimental Farm recorded during the 2005–07 growing seasons.






through 2007 growing seasons. According to the fog classification system used by Leipper (1994), heavy fog (visibility < 1 km), moderate fog (visibility 1–5 km), and light fog (visibility 5–11 km) occurred 7.1%, 12.9%, and 17.8%, respectively, at BBH during the 2005 through 2007 growing seasons. Heavy fog incidence at BBH was much more likely in the early morning and late evening hours than at mid-day (Fig. 2). Leaf-water sensors installed at BBH indicated that water deposition onto leaves occurred during virtually every incidence of fog recorded there. However, net water input to the soil during these fog hours was not indicated by either Watermark soil moisture transducers (in 2007) or time domain refractometers (2006–07). It is difficult to accurately determine the amount of water contributed by fog through the use of weighing lysimeters alone, both because of fog's quantitatively small input and because of the confounding effects of processes such as ET and dew formation that are likely occurring simultaneously. For instance, Fig. 3 illustrates the general pattern of hourly lysimeter weight changes at BBH based on all 2005 through 2007 growing season data. The pattern of lysimeter weight losses

FIGURE 3. Mean hourly lysimeter weight changes at Blueberry Hill Experimental Farm for the 2005–07 growing seasons.






and gains (Fig. 3) closely matches the pattern of fog occurrence (Fig. 2). This might suggest that fog was largely responsible for the observed positive changes in diurnal lysimeter weight. However, because fog of any kind occurred at BBH less than 20% of the time, and dense fog only 7.1% of the time, the pattern of positive changes in lysimeter weight illustrated in Fig. 3 was likely also due to dew formation in the absence of fog. Starr et al. (2004) found consistent nighttime increases in lysimeter weight at BBH in 2002, which they suggested might be due to dew formation and/or vapor deposition into the soil. The effect of fog deposition cannot be separated from that of dew formation because the presence of surface fog implies dew formation. Nevertheless, the additive effect of fog on the suppression of ET during non-rain hours can be approximated through a comparison of ET rates in the presence and absence of fog.

Overall, the net water equivalent contributed by fog at BBH was calculated by multiplying the difference between mean fog ET rates and non-fog ET rates by the total number of fog hours. When these values were normalized for a growing season having 338 hours of dense fog (the three-year mean for this study), BBH was calculated to receive an equivalent annual water input of approximately 13.5 cm (5.3 in.) from fog. By reducing the vapor pressure difference between a plant's surface and the atmosphere, fog acts to dramatically curtail the physical forces responsible for evapotranspiration. In addition, the possibility exists that lowbush blueberry leaves are capable of absorbing fog water directly through stomatal openings. Such absorbed water would likely be minimal as recorded by weighing lysimeters but could play a crucial role in xylem sap transport. A 2004 study by Burgess and Dawson showed that fog water can be directly absorbed by coastal redwoods (*Sequoia sempervirens*) through openings in their leaf surfaces. The current study, however, was not designed to address this process.

The results of this study are qualitatively consistent with other studies showing the importance of advection fog deposition to the water budgets of coastal ecosystems. In a three-year isotopic study on fog water input, Dawson (1998) determined that fog-drip off redwood trees contributed about 34% of the annual water input to northern coastal redwood forest soils. In that study, approximately 66% of all water used by understory plants during the summer months was estimated to have come from fog deposition. Similarly, Ingraham and Matthews (1995) used stable isotopic methods to show that water from advection fog deposition can infiltrate to the root zone in many coastal sites in Point Reyes, another northern California location with summer temperature and humidity conditions analogous to those existing during the summer months in coastal Maine. Though the amounts of water found to be contributed to the weighing lysimeters by fog in the current study were smaller than the amounts determined in the aforementioned studies along the northern California coast, fog nevertheless appears to play a role in the water budgets of Maine blueberry fields. The importance of this role and how it varies with coastal proximity and soil type is currently being evaluated at research sites both closer to and farther from the Maine coast.

## *Crop Coefficients*

Table 3 shows the calculated monthly $K_c$ values at both BBH sites for the three-year study period. An overall mean $K_c$ value of 0.69, with a standard error of 0.02, was calculated using 696 days of data from the two stations. An analysis of variance of the three-year data from May to September indicated that the monthly mean $K_c$ values were statistically similar for all months. The absence of a strong seasonal trend in the lowbush blueberry $K_c$ value indicates that the value of ~0.69 may be used by Maine growers throughout the entire growing season. In addition, analysis of variance revealed no differences between crop and prune-year $K_c$ values. The $K_c$ values for Addison were found to be similar (mean of 0.71

TABLE 3. Lowbush blueberry crop coefficient ($K_c$) values determined using daily weighing lysimeter and meterological data measured over three growing seasons at Blueberry Hill Experimental Farm, Washington County, Maine

| Month | Combined sites $K_c$ data days | BBH 1 $K_c$ data days | BBH 2 $K_c$ data days |
|---|---|---|---|
| May | 0.64 (0.04)[z] 145 | 0.61 (0.05) 73 | 0.68 (0.05) 72 |
| June | 0.70 (0.02) 138 | 0.67 (0.04) 68 | 0.74 (0.03) 70 |
| July | 0.69 (0.04) 149 | 0.68 (0.06) 73 | 0.70 (0.03) 76 |
| August | 0.74 (0.02) 136 | 0.74 (0.03) 66 | 0.74 (0.03) 70 |
| September | 0.65 (0.05) 128 | 0.62 (0.07) 68 | 0.69 (0.08) 60 |
| Overall mean | 0.69 (0.02) 696 | 0.67 (0.02) 348 | 0.73 (0.02) 348 |

[z]Standard error given in parentheses following mean $K_c$ value.

with a standard error of 0.02) to those of BBH but were not included in Table 3 because the lack of irrigation at Addison precluded an assurance that sufficient soil water was consistently available there to meet plant ET demands.

Although no estimates of lowbush blueberry $K_c$ values exist in the literature, the current study's calculated value of 0.69 is close to the optimum $K_c$ value of 0.75 determined by Byers and Moore (1987) for highbush blueberry in Arkansas. In contrast, Haman et al. (1997) determined $K_c$ values ranging from 0.20 to 0.35 for young Florida highbush blueberry, whereas Storlie and Eck (1996) found $K_c$ values to range between 0.19 and 0.27 for young New Jersey–grown highbush blueberry. These differences may reflect the impact of such factors as climate, soil, crop life-stage, and water availability on $K_c$ value. The significant effect of fog deposition on ET rate shown in the previous section suggests that proximity to the Maine coast, with its associated greater fog frequency and more moderate temperature, may alter the $K_c$ values determined in this study. As mentioned previously, we are currently evaluating these relationships at additional sites.

## SUMMARY AND CONCLUSIONS

A three-year study was conducted using weighing lysimeters to determine the ET rates of lowbush blueberry at two irrigated sites and one nonirrigated site within 7 km of the Maine coast. Climatic data consisting of hourly air temperature, relative humidity, solar flux, rainfall, and wind speed measurements were used to calculate grass reference evapotranspiration ($ET_o$) by the Penman-Montieth equation. The effects of fog and night/early morning dew deposition on ET suppression were also determined using both lysimeter and visibility data. For the irrigated fields at BBH, tensiometers were used to schedule irrigation in order to maintain a mean soil water potential of at least –20 kPa. This minimum soil potential ensured that water availability did not significantly limit ET rates at the BBH sites. In contrast, no irrigation was applied to a site located 5.8 km from BBH in Addison, Maine. Monthly ET rates for the irrigated and nonirrigated fields, as determined by four weighing lysimeters at each site, were found to be statistically similar. Mean weekly ET rates (with standard errors) for the three sites during June, July, and August averaged 2.12 (± 0.05), 2.34 (± 0.07), and 2.19 (± 0.07) cm/wk, respectively. These values are close to the traditional Maine grower "rule of thumb" recommending 2.54 cm of water per week during these months. The difference between the perceived required rainfall and the actual ET rates calculated in this study may be due to the coastal proximity of the experimental sites studied here. That is, ET rates typically encountered at more inland sites may be higher due to higher temperature and less fog.

Results of this study indicate that fog deposition plays a role in the water budget of Maine lowbush blueberry by reducing water demand. The extent of this fog-related ET suppression is reflected in the monthly and total $K_c$ values. The mean $K_c$ value (with standard error) when combined for all sites from May to September was found to be 0.69 (0.02). No differences were found in the $K_c$ values between the irrigated BBH sites and the nonirrigated Addison site. The $K_c$ value given in this study can be used in conjunction with meteorological data, such as solar flux and air temperature, to provide Maine lowbush blueberry growers with the ability to better predict water demand by their crop. Additional research is currently being conducted to determine how soil properties and coastal proximity might influence these $K_c$ values.

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